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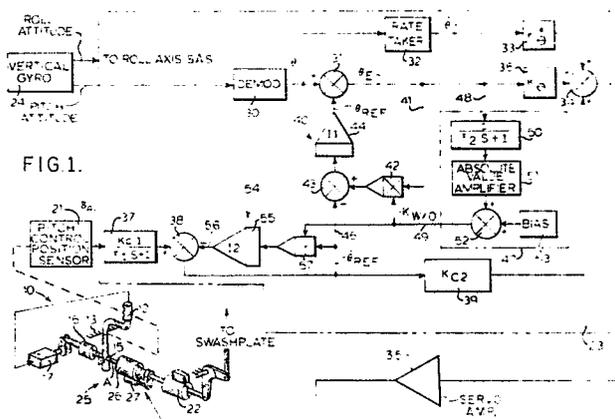
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Stability augmentation systems for navigable crafts.

A stability augmentation system utilising a limited authority series actuator (25) has an adaptive washout circuit (40) which automatically reduces the effective washout system washout time constant as a function of attitude error or series actuator displacement. For small errors and for disturbances due to gusting winds, the system washout time constants are slow, thus providing good stability. For large errors the circuit smoothly reduces the time constants to keep the series actuator (25) from saturating.



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STABILITY AUGMENTATION SYSTEMS
FOR NAVIGABLE CRAFTS

The invention relates to stability augmentation systems for navigable craft particularly, but not exclusively, those associated with flight control systems for aircraft.

Prior art automatic pilots are known that utilise
5 stability augmentation systems (SAS) for providing short terms stability augmentation about the various axes of the aircraft. Such systems normally utilise limited authority series actuators which operate in response to sensors such as rate gyroscopes or vertical gyroscopes providing derived
10 rate signals. However, as is known, when an aircraft utilising such a system executes a manoeuvre, large errors can exist within the stability augmentation system which can cause the series actuator to saturate, resulting in an abrupt change in the aircraft's handling characteristics. Although this problem is common to both helicopter and
15 fixed wing stability augmentation systems, changes in handling characteristics are much more noticeable in a helicopter because a helicopter is inherently unstable and difficult to fly. In a helicopter, the stability
20 augmentation system typically relies on a signal from a cyclic pitch stick position transducer and from a vertical gyroscope to drive a limited authority series actuator (short throw hydraulic or electric servo). The series actuator makes minor corrective adjustments to a swash plate
25 in order to stabilise the aircraft. The authority of the actuator, and thus of the stabilising adjustments to the swash plate, are typically on the order of $\pm 10\%$ of the cyclic pitch stick's authority, thus it is desirable that the series actuator remain relatively centred in its range
30 of authority. This is not always possible as the pilot may initiate a trim change greater than the authority of the actuator, thus rendering the actuator grossly uncentred and no longer within its symmetrical operating range.

It is known in the art to provide a washout circuit

for generating a signal to drive the series actuator back into its centred or symmetrical operating range. The conventional washout circuit operates with a relatively slow time constant, since it is generally undesirable to have the washout circuit attempting to washout or compensate for small high frequency displacements of the series actuator generated in compensating response to air turbulence. After large trim changes or other gross manoeuvres, it is necessary quickly to recentre the series actuator by placing the actuator drive circuitry in a fast washout condition. In the prior art, this has been done by manually depressing a force trim release button located on the cyclic pitch stick, or by tripping detent switches which trigger the fast washout condition. The transition from slow to fast washout with this known arrangement is often abrupt, reflected in radical changes in aircraft handling characteristics. In the fast washout condition, much shorter time constants are used so that the series actuator is quickly centred, but the aircraft also becomes less stable.

In addition to triggering the fast washout condition, the force trim release button also actuates a clutch for recentring the conventional feel spring mechanism to its zero force position. The feel spring mechanism is used to impart artificial manual flight control reactions to the human pilot via the stick, as is well known. A problem with this arrangement is that when hovering, particularly at very low altitudes, it may be desirable to fly with the feel spring mechanism disengaged to improve the pilot's reaction time. However, with the feel spring mechanism disengaged, it is no longer convenient to use the force trim release button to actuate the fast washout condition. Thus there is a need for a washout circuit which operates automatically and not associated with the force trim release mechanism. Furthermore, it is desirable that the washout circuit make a gradual transition from slow to fast so that abrupt changes in aircraft response are eliminated.

According to the present invention there is provided a stability augmentation system for a navigable craft including body mounted attitude sensor means for providing an attitude signal representative of motion of the craft about an axis thereof, the system comprising actuator means responsive to the attitude signal for stabilising the craft about said axis, the actuator means having a limited displacement capacity from a reference position and tending to reach the limit of the displacement capacity in response to large amplitude error signals, and manoeuvre control means for manoeuvring the craft about the axis, characterised in that the system further comprises apparatus for preventing the actuator means from reaching said limit, the apparatus comprising error sensing means responsive to the attitude signal and to the manoeuvre control means for providing an error signal for driving the actuator means, first washout means coupled to the actuator means for providing a first washout signal of opposite polarity to the error signal and of variable magnitude, so as to reposition the actuator means towards the reference position, and control means providing a control signal for controlling the magnitude of the washout signal in accordance with the displacement of the actuator means, the control signal causing the magnitude to increase as the displacement approaches said limit.

It will be seen that the present invention provides an adaptive washout for automatically recentring an actuator, such as a series actuator, of a stability augmentation system. The washout time constant is continuously variable as a function of actuator displacement or attitude error. The invention comprises error sensing means responsive to an attitude sensor, such as a rate gyroscope or vertical gyroscope, and also responsive to a position sensor coupled to a conventional pilot operated manoeuvre control system, such as a control stick. The error signal is applied to a limited authority series actuator of the stability augmentation system which in turn adjusts a control surface to stabilise the craft. The washout circuit provides a washout signal of opposite polarity to the error signal and

of a variable magnitude depending on the relative displacement of the series actuator. The system further comprises means for controlling the magnitude of the washout signal in accordance with displacement of the actuator so that the magnitude increases as the actuator approaches the limits of its authority or its capacity. The washout circuit thereby provides a gradually increasing washout gain, or in other words, a gradually decreasing washout time constant, for relatively large amplitude error signals which would otherwise drive the series actuator towards the limits of its authority and into saturation.

A helicopter control system employing a stability augmentation system in accordance with the present invention will now be described in greater detail, by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic block diagram of the control system and

Figure 2 is graph showing the relationship between washout gain and actuator displacement.

The present invention is applicable to a wide variety of navigable craft having numerous types of limited authority stabilisation system as well as a wide variety of long term reference sources. For purposes of description, the invention will be explained in terms of a helicopter having a stability augmentation system (SAS) with a limited authority series actuator for providing short term stability augmentation of the aircraft. Although the invention is applicable to the control of a plurality of aircraft types about a plurality of axis, the invention will be described with regard to one axis of the aircraft type, i.e. the pitch axis of the helicopter.

Referring to Figure 1, a portion of a typical helicopter manoeuvre control system is illustrated at 10, the system including a cyclic pitch stick 12 which is illustrated as schematically mounted to the helicopter airframe 13 to impart control motion to a connecting rod 15. Connected to the connecting rod 15 is a conventional feel spring mechanism 16 to impart artificial manual flight

control reactions to the human pilot via the stick 12 in a well known manner. The central or zero force position for the mechanism 16 is determined in a conventional manner by a force trim release clutch mechanism 17 through
5 appropriate linkages. The trim mechanism 17 is actuated in a well known manner by manipulation by the human pilot of a conventional force trim release button on the grip of the cyclic pitch control stick 12. A pitch control stick position sensor or transducer 21 is coupled to the
10 control stick 12 to provide a signal representative of the displacement of the stick 12 from a central position. The output of the transducer 21 may be provided in terms of either stick force, stick displacement, or the like, in a well known manner. The output of the connecting rod 15 is
15 applied to the input of a conventional power boost actuator 22 which, in turn, applies control motion to the helicopter swash plate via appropriate linkages.

In order to provide short term stabilisation of the helicopter, a stability augmentation system (SAS) is
20 included comprising a stability augmentation circuit 23, a vertical gyroscope 24 and a limited authority SAS actuator 25. The limited authority actuator 25 may be of the type disclosed in U.S. Patent Specification No.3,269,199. The actuator 25 includes a motor 26 and a feedback device such
25 as a potentiometer 27 which provide a signal in accordance with the position of the actuator 25. The actuator 25 is appropriately fastened to the connecting rod 15 on one end thereof and provides its output to the power boost actuator 22 at the other end thereof. Thus it will be appreciated
30 that the actuator 25 is connected as a series element in the system as illustrated, but may be installed in other manners to achieve the same effect. The actuator 25 has a movable piston output which can extend and retract in such a way as to move the swashplate without moving the pilot's
35 controls. The actuator's authority is generally small compared to that of the pilot's control input. For example, the cyclic pitch stick might move a point designated by the

letter A in Figure 1, a total of 50mm when going to full aft to full forward. The actuator 25 when going from full retract to full extend might move the same point a total of 10mm. The actuator is said to have an authority of plus or minus 10%. As is well known, it is preferable to operate the series actuator at its relatively centred position between the corresponding fully extended and fully retracted position. When the displacement of the actuator 25 reaches one of these limits, it is said to be saturated and the aircraft's operating characteristics change dramatically.

For the pitch axis stability augmentation exemplified in Figure 1, the vertical gyro 24 provides a pitch displacement signal or pitch attitude signal to a demodulator 30 which provides an attitude signal θ representative of the pitch attitude of the aircraft.

The pitch attitude signal θ from the demodulator 30 is applied to the input of a summing junction 31 and also is applied as an input to a rate taking circuit 32 which provides an attitude rate signal $\dot{\theta}$ reflecting short term changes in the pitch attitude signal θ . The output of rate taker 32 is processed through gain scaling circuitry 33 to impart a gain scale factor $K_{\dot{\theta}}$. The output of the gain scaling circuit 33 is applied to one input of summing junction 34 whose output is in turn applied as an input to a conventional servo amplifier 35. The output of the summing junction 31, which may be considered as representative of an attitude error θ_E , is processed through a gain scaling circuit 36 which imparts a gain scale factor of K_{θ} to the attitude error signal. This gain scaled attitude error signal is applied to another input of the summing junction 34. The output of the servo amplifier 35 is applied to drive the motor 26 of the actuator 25 in the usual fashion. Thus it will be appreciated that the components 31 to 36 comprise the servo system for driving the actuator 25 in accordance with pitch information derived from the vertical gyro 24.

The output of the pitch control stick position transducer 21 provides an output δ_{θ} which is applied to a shaping network 37 which provides lag compensation according to the transfer function shown within the block. The output of the shaping network 37 is applied as an input to a summing junction 38 the output of which is applied to a gain scaling circuit 39 which imparts a gain scale factor K_{C2} . The gain scaled output of the circuit 39 is applied as another input to the summing junction 34, thereby providing a direct path, subject to the parameters of shaping network 37 and gain scaling circuit 39, between the pitch control position sensor 21 and the servo amplifier 35. It will be appreciated that this direct path provides increased response sensitivity.

The invention includes a first washout circuit 40 which receives the attitude error signal θ_E via a lead 41, which signal is applied to the input of a multiplier circuit 42 the output of which is applied as one input to a summing junction 43. The output of the summing junction 43 is applied to a first integrator 44 the output of which is in turn applied to a negative or inverting input 45 of the summing junction 31. A signal from the output of the summing junction 38 is applied via lead 46 as another input to the summing junction 43. This signal, hereinafter referred to as reference signal θ_{ref} , serves as a pitch rate reference input to the integrator 44.

An adaptive washout biasing circuit, or control circuit 47, receives the attitude error signal θ_E on a lead 48 and provides a washout control signal $K_{W/O}$ on a lead 49 which is in turn applied as an input to the multiplier 42. The washout control circuit 47 comprises a shaping network 50 for providing lag compensation according to the transfer function shown within the block. The output of the shaping network 50 is applied to an absolute value amplifier 51 which provides an absolute value signal in proportion to the magnitude of the attitude error signal θ_E . The output of the absolute value amplifier 51 is applied as an input to a summing junction 52 the output of which is the washout

control signal $K_{w/o}$ on lead 49. Also applied to the summing junction 52 is a bias signal, such as a d.c. voltage, for providing a nominal washout control signal when the attitude error signal θ_E is of small magnitude.

5 The invention further includes a second washout circuit 54 which comprises a second integrator 55 the output of which is applied to a negative or inverting input 56 of the summing junction 38. A multiplier 57 receptive of the reference signal θ_{ref} on lead 46 and also receptive of the
10 washout control signal $K_{w/o}$ provides a control signal to the integrator 55 of the second washout circuit.

According to the usual practice, the error sensing circuit including the summing junction 31 is provided with a reference signal θ_{ref} at the negative or inverting
15 terminal 45 thereof. This is needed to assure that the stability augmentation system will not countermand the pilot initiated manoeuvres. This reference signal is produced by integrating the reference signal θ_{ref} on line 46 through the integrator 44, and in practice the
20 parameters (K_{C1} , K_{C2} , and τ_1) of shaping network 37 and scaling circuit 39 are selected such that for most manoeuvres the reference signal θ_{ref} is equal to the pitch attitude signal θ . Thus for most manoeuvres, the error signal θ_e is equal to zero. This achieves the desired
25 result of inhibiting any sensed attitude changes from opposing the pilot selected manoeuvre. Furthermore, because the attitude error signal θ_e on the lead 48 is at, or near, zero during most manoeuvres, the washout control signal $K_{w/o}$ on line 49 is dominated by the bias voltage 53.

30 It will be seen that the series actuator 26 is driven by the servo amplifier 35 in response to the attitude error signal θ_e . Thus the attitude error signal is a measure of the actuator displacement. Furthermore, since the attitude error signal θ_e is applied to the washout control
35 circuit 47 on lead 48, the washout control signal on lead 49 is dependent on the attitude error. The washout control signal $K_{w/o}$ may be seen as directly affecting the washout gain of washout circuits 40 and 54 in the sense that

increasing the control signal tends to increase the washout rate from a relatively slow washout condition to a relatively fast washout condition. The washout gain parameter is often expressed in terms of its reciprocal
5 $1/K_{w/o}$, called the washout time constant.

Referring to Figure 2, the magnitude of the washout gain is plotted along the abscissa as a function of actuator displacement. From Figure 2 it will be seen that for zero actuator displacement, that is for zero attitude
10 error, the washout gain takes on a nominal value as provided by the bias voltage 53. This nominal value may be for example, 0.1 sec.^{-1} . In terms of the washout time constant, this nominal washout gain corresponds to a washout time constant of the order of 10 seconds. In this
15 slow washout condition, any short term displacement of the aircraft about the relevant axis, due to gusting winds for example, will be sensed by the vertical gyro 24, which will in turn produce a non zero attitude error θ_e and attitude rate $\dot{\theta}$. This will cause the servo amplifier to drive the
20 linear actuator 25 in a well known manner to compensate for the gust and retrim the craft. The shaping network 50 is selected to have lag compensation parameters which will filter out the short term attitude error signals, as caused by gusting winds for example. Thus the washout control
25 circuit 47 is relatively insensitive to such short term attitude error signals. For example, the shaping network 50 may have lag delays of approximately 1/2 to 1 second, or in other words, a non-zero attitude error condition needs to exist for longer than 1/2 to 1 second for the
30 washout control circuit substantially to effect any change in the washout gain or time constant. Should a sustained attitude error signal exist, due to a minor trim change for example, the servo amplifier 35 will initially drive the actuator 25 off centre from its reference position.
35 However, the washout circuit 44 begins to inject a signal of opposite polarity to the attitude error signal which ultimately drives the actuator back towards its centred position.

The attitude error signal θ_e is multiplied by the washout control signal $K_{w/o}$ in the multiplier 42. It will be appreciated that the product thus formed is proportional to the square of the attitude error signal θ_e and has the same sense or polarity as the attitude error signal.

5 Integrating this product through the integrator 44 produces a washout signal which increases in magnitude according to the integration process, whilst retaining the same sense or polarity of the attitude error signal. This washout

10 signal is then subtracted from the error signal in the summing junction 31. Thus it will be seen that the washout signal acting through the summing junction 31 opposes the polarity of the error signal. Because the magnitude of the washout signal is essentially proportional to the square of

15 the error signal, the washout signal dominates, thereby repositioning the series actuator 25 towards its centred or referenced position.

To assure that the pilot selected manoeuvres are not countermanded by the stability augmentation system, the reference signal θ_{ref} is applied to the summing junction 43. As was stated earlier, the reference signal θ_{ref} is selected so that when the pilot manoeuvres the aircraft, the output of the integrator 44 (θ_{ref}) is equal to the pitch attitude 0. This is accomplished by properly selecting the constants

25 K_{C1} , K_{C2} , and τ_1 according to well known linear aircraft models. However, as is also well known, for gross manoeuvres such as steep banked turns, or during large power changes such as changing the throttle setting or changing the collective pitch stick setting, the abovementioned

30 parameters may no longer be adequate to assure that the error signal θ_e remains at or near zero. This results in large attitude errors which, if remained unchecked, will saturate the series actuator 25, driving it to its displacement limits. However, before this can occur the large attitude

35 signal θ_e is sensed by the washout control circuit control 47 which provides an increased washout signal according to Figure 2. Because of the non-linear, or square law, effect



of the multiplier 42 a washout signal is generated having a much shorter time constant which quickly recentres the series actuator 26. It will be seen that the washout control signal $K_{w/o}$ is also applied to the second washout circuit 54 so that the pitch control position signal δ_{θ} is synchronised to the new trim position. For example, should the pilot drop the collective stick (not shown) which will cause the aircraft to nose down, certain cross coupling effects require that the cyclic pitch stick 12 be adjusted to produce an aft cyclic signal δ_{θ} . However, the pitch attitude θ is not changing and, therefore, the referenced signal θ_{ref} , resulting from the aft cyclic signal δ_{θ} , will tend to saturate the series actuator unless washed out by the washout circuit 54.

Thus it will be seen that the present invention provides a circuit for automatically reducing the effective system washout time constant $1/K_{w/o}$ as a function of attitude error. Whilst the circuit has been explained in terms of analogue block diagram elements, in practice digital circuit techniques may be implemented. Furthermore, whilst Figure 2 exemplifies a typical washout gain versus attitude error function, the specific gain values and the slope of the resulting function may vary from aircraft to aircraft. In this regard, Figure 2 illustrates the general principles, namely, that for small errors and for disturbances of sufficiently high frequency so as to be filtered by the compensation network 50, the system washout time constants are slow. This provides the needed low frequency bandwidth necessary for good stability under typical gusting conditions. On the other hand, should a pilot initiate a manoeuvre to cause a large attitude error to exist, the circuit smoothly reduces the time constants to keep the actuators from saturating.

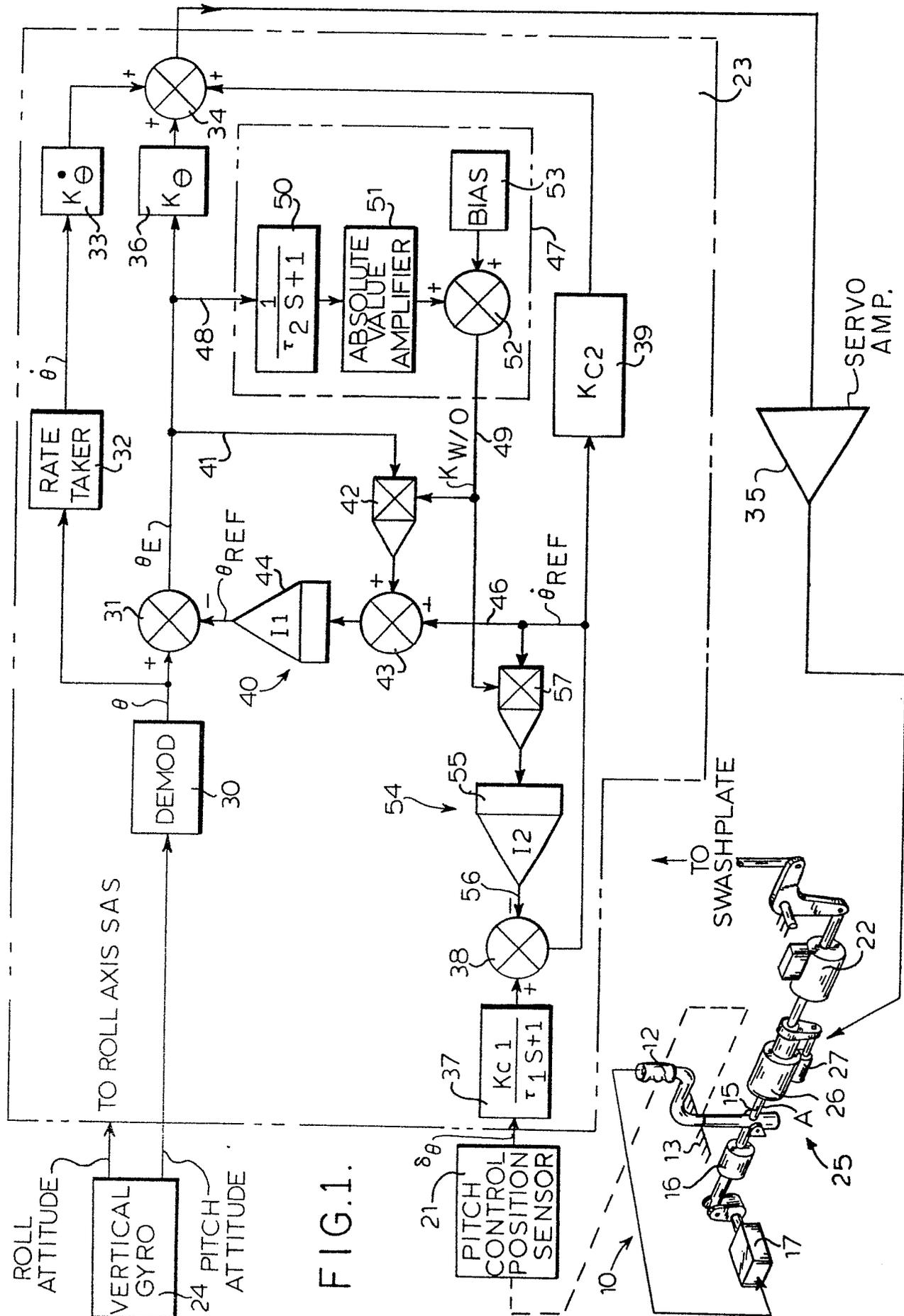
CLAIMS

1. A stability augmentation system for a navigable craft including body mounted attitude sensor means for providing an attitude signal representative of motion of the craft about an axis thereof, the system comprising actuator means responsive to the attitude signal for stabilising the craft about said axis, the actuator means having a limited displacement capacity from a reference position and tending to reach the limit of the displacement capacity in response to large amplitude error signals, and manoeuvre control means for manoeuvring the craft about the axis, characterised in that the system further comprises apparatus for preventing the actuator means (25) from reaching said limit the apparatus comprising error sensing means (31) responsive to the attitude signal and to the manoeuvre control means (12) for providing an error signal for driving the actuator means (25), first washout means (40) coupled to the actuator means (25) for providing a first washout signal of opposite polarity to the error signal and of variable magnitude so as to reposition the actuator means (26) towards the reference position, and control means (47) providing a control signal for controlling the magnitude of the washout signal in accordance with the displacement of the actuator means (25), the control signal causing the magnitude to increase as the displacement approaches said limit.
2. A system according to claim 1, characteristic in that the control means (47) includes means (50) responsive to the error signal.
3. A system according to claim 2, characteristic in that the means responsive to the error signal comprises first lag compensation means (50).
4. A system according to any of the preceding claims, characteristic in that the control means (47) further includes means (51) responsive to the error signal for providing an absolute value signal in proportion to the magnitude of the error signal.

5. A system according to any of the preceding claims, characteristic in that the control means (47) further includes means (53) for providing a bias signal.
6. A system according to any of the preceding claims,
5 characteristic in that it further comprises first multiplier means (42) responsive to the error signal and to the control signal for providing a first product signal for varying the magnitude of the first washout signal.
- 10 7. A system according to claim 6, characteristic in that the first washout means (40) is responsive to the first product signal.
8. A system according to any of the preceding claims,
15 characteristic in that it further comprises position sensing means (21) responsive to the manoeuvre control means (12) for providing a position signal.
9. A system according to claim 8, characteristic in that it further comprises second washout means (54) responsive to the control signal for providing a second washout signal
20 of opposite polarity to the position signal.
10. A system according to claim 8 or 9, characteristic in that it further comprises means (43) for coupling the position signal to the first washout means (40).
11. A system according to any of claims 8 to 10,
25 characteristic in that it further comprises second lag compensation means (37) responsive to the position signal.
12. A system according to claim 11, characteristic in that the second lag compensation means (37) is coupled to the first washout means (40) for providing a position reference
30 signal to the latter.
13. A system according to any of claims 8 to 12, characteristic in that it further comprises means (37, 38, 39, 34, 35) for coupling the position signal to the actuator means (25).

14. A system according to claim 13, characteristic in that the means for coupling the position signal to the actuator means (25) includes means (39) for gain scaling the position signal.

5 15. A system according to claim 9 and any claim appended thereto, characteristic in that it further comprises second multiplier means (57) responsive to the position
10 signal and to the control signal for providing a second product for varying the magnitude of the second washout signal.



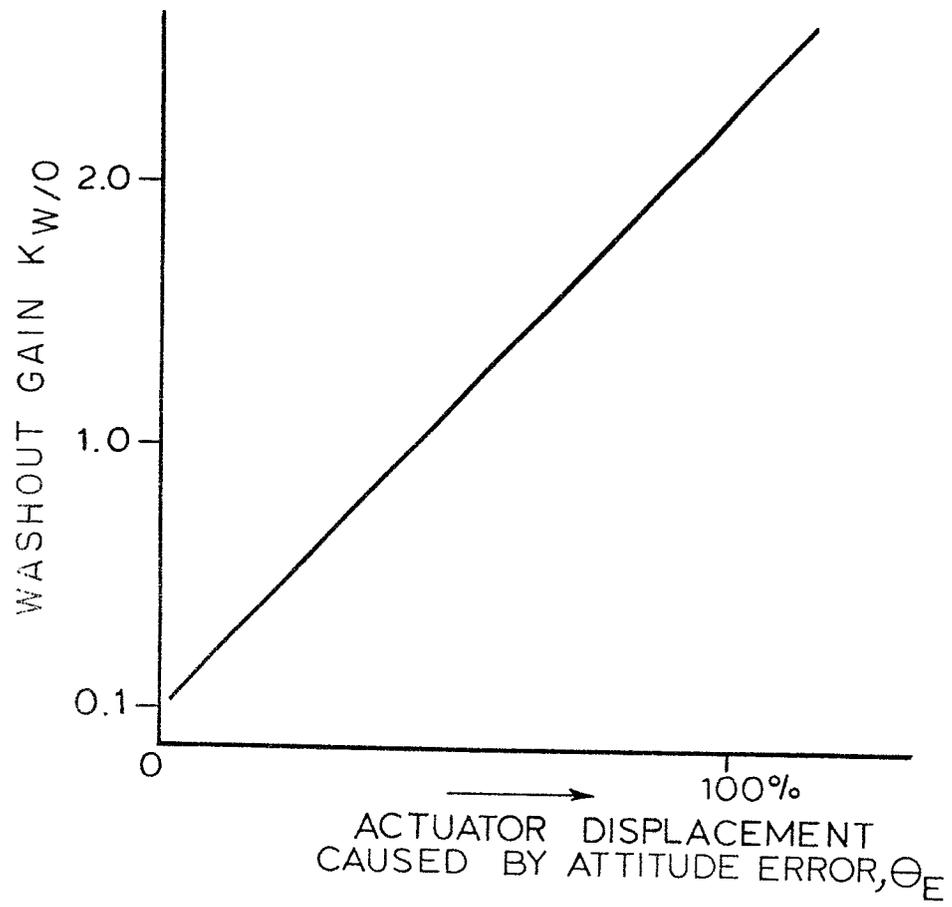


FIG. 2.



European Patent
Office

EUROPEAN SEARCH REPORT

0088614

Application number

EP 83 30 1193

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 3)
A	US-A-4 109 886 (E. TRIBKEN) -----		G 05 D 1/08
			TECHNICAL FIELDS SEARCHED (Int. Cl. 3)
			G 05 D
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 17-06-1983	Examiner HELOT H.V.
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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